JOURNAL OF SURGICAL RESEARCH 39, 369–377 (1985)

582

The Effect of Portacaval Shunt on Hepatic Lipoprotein Metabolism in Familial Hypercholesterolemia[1]

JEFFREY M. HOEG, M.D.,[2] STEPHEN J. DEMOSKY, JR., B.A., ERNST J. SCHAEFER, M.D., THOMAS E. STARZL, M.D.,* KENDRICK A. PORTER, M.D.,† AND H. BRYAN BREWER, JR., M.D.

*Molecular Disease Branch, National Heart, Lung, and Blood Institute, National Institutes of Health, Bethesda, Maryland; and *The Department of Surgery, University of Pittsburgh School of Medicine, Pittsburgh, Pennsylvania; and †St. Mary's Hospital School of Medicine, London, United Kingdom*

Submitted for publication April 16, 1984

The hyperlipidemia observed in familial hypercholesterolemia can be reduced by portacaval anastomosis. We report the effects of a portacaval shunt on hepatic morphology and biosynthetic pathways crucial to hepatic cholesterol homeostasis in homozygous receptor-negative familial hypercholesterolemia. Portacaval anastomosis was associated with a dramatic change in hepatocyte morphology, 28% reduction in plasma low-density lipoprotein concentration, and a decrease in hepatic total and free cholesterol content by 27 and 75%, respectively. Furthermore, the rate-limiting enzyme in cholesterol biosynthesis, 3-hydroxy-3-methylglutaryl coenzyme A reductase was decreased by 56%. Finally, the reduced binding of low-density lipoproteins to hepatic membranes preoperatively was increased following the portacaval shunt. These combined results indicate that the changes in circulating lipoprotein concentrations observed after portacaval shunt are due to alterations in the metabolic consequences of the defective recognition of low-density lipoproteins by the liver of familial hypercholesterolemic subjects.

INTRODUCTION

The mammalian liver plays a central role in lipid and lipoprotein metabolism. It is the primary site for endogenous cholesterol and lipoprotein biosynthesis as well as the principal organ for cholesterol excretion through bile and bile acid formation [11, 18, 48]. Studies in rats [9, 19, 54], swine [33], and rabbits [27, 34] indicate that a significant portion of an injected dose of radiolabeled low-density lipoproteins[3] is removed by the mammalian liver. The initial step in the cellular uptake of circulating LDL is the binding of the lipoprotein to a receptor in the plasma membrane [8, 15]. Isolated hepatic membranes from a number of animal species have been shown to contain a receptor which [1, 23, 26, 28, 55] specifically binds LDL. Recently, hepatic membranes from normal adult humans have also been demonstrated to bind LDL [16, 22]. Thus, coordinate control of lipoprotein uptake, catabolism, and synthesis may occur in normolipidemic man.

Familial hypercholesterolemia is an autosomal dominant disorder characterized clinically by hypercholesterolemia, xanthomas, and premature atherosclerosis [24]. By analysis of skin fibroblasts from patients homozygous for FH, Brown and Goldstein determined that FH was due to one of several mutations in the gene coding for the cellular receptor for LDL [7, 51]. The most frequent allelic mutation resulting in FH is the loss of the functional high-affinity receptor for LDL and is referred to as receptor-negative FH [51]. We have recently demonstrated that the loss of the fibroblast

[1] A preliminary account of this work was presented at the American Federation for Clinical Research Meetings held in Washington, D. C., May 1983.

[2] To whom correspondence should be addressed: Molecular Disease Branch, National Heart, Lung, and Blood Institute, National Institutes of Health, Building 10, Room 7N117, Bethesda, Md. 20205.

[3] Abbreviations used: FH, familial hypercholesterolemia; LDL, low-density lipoproteins; SE, standard error of the mean; PBS, phosphate-buffered saline; BSA, bovine serum albumin; TrisCl, tris (hydroxymethyl)aminomethane; ^{125}I-LDL, ^{125}I-labeled low-density lipoproteins; VLDL, very-low-density lipoproteins; LPDS, lipoprotein-deficient serum; HMG-CoA reductase, 3-hydroxy-3-methylglutaryl coenzyme A reductase; apoB, apolipoprotein B.

0022-4804/85 $1.50

LDL receptor in FH homozygotes is paralleled by a defect in the hepatic membrane recognition of LDL [22]. Therefore, the profound hypercholesterolemia and accelerated atherosclerosis observed in FH may occur as a result of the loss of the hepatic LDL receptor and the resulting changes in hepatic lipid and lipoprotein metabolism.

Patients with FH frequently are refractory to all lipid lowering drug regimens. However, the use of a portacaval anastomosis to shunt blood flow from the liver has been shown to be effective in lowering the plasma lipids in these patients [42]. The present studies were performed on hepatic tissue in a receptor-negative FH subject to evaluate the effect of the portacaval shunt on both the binding of LDL to hepatic membranes as well as to assess the impact of the portacaval shunt on hepatic cholesterol metabolism.

METHODS

Patient history. The patient studied was first noted to be hypercholesterolemic at the age of 13. Despite therapeutic trials of cholestyramine, niacin, hydroxymethylglutamic acid, and neomycin, the plasma cholesterol ranged from 915 to 1210 mg/dl and she developed symptomatic coronary artery disease. The patient's mother (age 40) had a plasma cholesterol of 462 mg/dl and an LDL cholesterol of 359 mg/dl. The patient's father was not available for study. Analysis of LDL binding in skin fibroblasts of TH demonstrated no detectable receptor for LDL [22]. Therefore, the patient's genetic, clinical, and biochemical profiles were consistent with the diagnosis of receptor-negative FH.

At age 21, after suffering two myocardial infarctions and receiving a double coronary artery bypass graft, the patient received a therapeutic portacaval anastomosis at the University of Pittsburgh in an effort to lower the plasma lipid concentrations. A liver biopsy taken at the time of the anastomosis provided the basis for the biomedical and histopathologic studies referred to as "preshunt" values. Three months after the initial surgery, hepatic tissue was obtained; informed consent had been given. Biochemical and morphologic studies performed on this tissue are referred to as "postshunt" values.

The hepatic tissues from normolipidemic control subjects were obtained at the time of laparotomy for kidney donation for renal transplantation. All hepatic biopsies were performed after informed consent had been given and the protocol used for hepatic biopsy and portacaval anastomosis was approved by the human experimentations committee at the University of Pittsburgh School of Medicine.

Lipoprotein preparation. Preparation of human LDL (d 1.030–1.050) was from 500 ml plasma collected in 0.01% EDTA by plasmapheresis from fasting, healthy volunteers. Lipoproteins were separated by preparative ultracentrifugation at 4°C for 16–24 hr [17] using KBr for density gradient adjustment [36]. These subfractions were then dialyzed 34 hr at 4°C against 150 vol of phosphate-buffered saline (pH 7.0) (GIBCO, Grand Island, N. Y.). Each isolated lipoprotein fraction was sterilized by 0.45-μm Millipore filtration (Millipore Corp., Bedford, Mass.) and used within 1 month of preparation. ^{125}I-LDL was prepared by the iodine monochloride method [31] as modified for lipoproteins [4]. A 25–30% efficiency of iodination was obtained and less than 6% of the radioactivity was soluble in the organic phase following a chloroform–methanol extraction. After dialysis over 24 hr at 4°C against 500–600 vol PBS, specific activities ranged from 2.7 to 4.6 $\times$ 10^9 Bq/ml LDL protein. The LDL protein concentration was determined by the method of Lowry *et al.* [30] using bovine serum albumin standard. After Millipore filtration, ^{125}I-LDL was stored at 4°C and used within 2–3 weeks of preparation.

Liver membrane preparation. Biopsy specimens were immediately placed in a beaker and all processing occurred at 4°C similar to that described by others [1, 2]. After mincing the tissue with a razor blade, it was washed with an ice-cold buffer containing 0.9% (w/v) NaCl, 1 m*M* EDTA, and 10 m*M* TrisCl (pH 8.0). Homogenization was performed by six

strokes of a motor-driven Teflon pestle in a buffer containing 0.25 *M* sucrose, 1 m*M* EDTA, and 10 m*M* TrisCl (pH 8.0). The homogenized preparations (10 mg/ml) were centrifuged for 10 min at 1000*g*. The supernatant solution was recentrifuged for 25 min at 10,000*g*, followed by ultracentrifugation at 100,000*g* for 60 min. The pellet from this ultracentrifugation was resuspended in a buffer containing 150 m*M* NaCl, 10 m*M* TrisCl (pH 8.0), and flushed through a 22-gauge needle 10 times. These membranes were recentrifuged for 15 min at 100,000*g* and the membrane pellets were then frozen in dry ice and stored in liquid nitrogen until used for binding assays and quantitation of HMG-CoA reductase activity. The 10,000*g* supernatant was used for cholesteryl esterase assays.

Lipoprotein quantitation. Blood was obtained in 0.01% EDTA from patient TH after a 12- to 14-hr overnight fast, and the plasma was separated at 4°C in a refrigerated centrifuge. Plasma cholesterol and triglycerides were quantitated on a Gilford 3500 using previously described enzymatic methods [32, 52]. HDL cholesterol was determined following dextran–sulfate precipitation of plasma. Plasma was ultracentrifuged (1.006 g/ml) for 18 hr at 39,000 rpm (4 °C) in Beckman 40.3 rotors (Beckman, Fullerton, Calif.) and the VLDL was separated from the other plasma lipoproteins by tube slicing [17]. The cholesterol concentration in the 1.006 g/ml infranate was measured, and the VLDL and LDL cholesterol were calculated.

Hepatic cholesterol and cholesteryl ester determination. Liver biopsy samples from normal and familial hypercholesterolemic subjects were weighed, extracted three times with chloroform–methanol (2/1 v/v) at 41°C. The samples were then extracted overnight with chloroform–methanol (2/1 v/v) at 30°C. The chloroform–methanol extracts were blown to dryness and the liquid was resuspended in 2-Propanol (J. T. Baker Chemical Co., Phillipsburg, N. J.). Free and total cholesterol were then measured by the enzymatic, fluorimetric method of Heider and Boyette [20]. Esterified cholesterol was determined as the difference between total and free cholesterol. The nanomoles of cholesterol extracted from the biopsy samples were normalized to initial sample weight.

Hepatic enzyme activities. The activity of HMG-CoA Reductase (EC 1.1.1.34) was quantitated in the 100,000*g* pellet, as previously described [3]. The cholesteryl ester hydrolase activity (EC 3.1.1.13) was determined in the cytosolic fraction at both pH 4.0 and pH 7.0 [21].

Binding of ^{125}I-LDL to liver membranes. Hepatic membrane binding of ^{125}I-LDL was assessed using previously described methods [1, 22, 28]. Briefly, frozen liver membrane preparation was thawed and resuspended in 50 m*M* NaCl, 30 m*M* Tris–HCl (pH 7.5) buffer (10–12 mg/ml) and passed through a 22-gauge needle. Membranes were then sonicated by five 4-sec pulses at the 55-W setting using an ultrasonics microtip (Heat Systems Ultrasonics, Inc., Plainview, N. Y.). From 100 to 200 μg membrane protein was then added to a 50 m*M* NaCl, 20 m*M* Tris–Cl (pH 7.5) buffer containing 1 m*M* $CaCl_2$. ^{125}I-LDL was added at the indicated concentrations with or without unlabeled LDL with a total assay mixture volume of 0.1 ml. Incubations were carried out at 37°C for 30 min at which time preliminary studies had demonstrated that equilibrium had been reached. Bound ^{125}I-LDL was separated from free ligand by a 3 min, 100,000*g* centrifugation of 50 μl of the assay mixture through 125 μl PBS in a 30°C angle rotor in an air-driven ultracentrifuge (Beckman, Palo Alto, Calif.). The supernatant was removed from the pellet by vacuum aspiration, and the pellet was washed once with 125 μl of PBS. The cellulose nitrate tube tips containing the membrane pellet were sliced and the radioactivity in the pellet quantitated in a Biogamma II scintillation counter (Beckman). Specifically bound ^{125}I-LDL was defined as the difference in ^{125}I-LDL quantitated in samples which were incubated with and without 390 μg of unlabeled LDL.

Histopathologic studies. One sample of each liver specimen was fixed in 10% neutral formalin and was then processed for examination

by light microscopy. A second piece of the biopsy tissue was fixed in buffered glutaraldehyde, postfixed in osmium tetroxide, and then embedded in epoxy resin (Epon 812). Some of the liver postshunt tissue was also postfixed in osmium and processed for electron microscopy. Ultrathin sections were stained with lead citrate and examined in a Phillips 300 electron microscope. The sizes of the mid-zonal hepatocytes before and after portal diversion were determined on hematoxylin and eosin-stained sections by a method previously described [43]. Mid-zonal hepatocytes identified in 1.0-μm-thick epoxy resin sections were also used for measuring the length of rough endoplasmic reticulum per area of cytoplasm by a morphometric method [29].

Statistical methods. Statistical comparisons of paired and unpaired lipoprotein determinations and biochemical assays were made using two-tailed t tests assuming the samples were independent [39].

RESULTS

The effects of portacaval shunt on the lipid and lipoprotein concentrations in the plasma in FH are summarized in Table 1. All of the lipid and lipoprotein concentrations decreased following the portacaval shunt. The decline of 291 mg/dl in total cholesterol and 266 mg/dl in the LDL cholesterol represented a 28% change ($P < 0.01$). Although the concentrations of VLDL, HDL, and total triglycerides also declined, these changes were not statistically significant.

These changes in lipoprotein concentration were paralleled by striking alterations in hepatocyte morphology (Fig. 1). Before portacaval diversion the hepatocytes were enlarged and their cytoplasm was vacuolated. Lipid deposits were demonstrated by staining frozen sections with Sudan IV. Ultrastructurally, the cytoplasmic droplets possessed a double membrane. The amounts of rough and smooth endoplasmic reticulum were normal. Free polyribosomes were also present in the cytoplasm. Glycogen was abundant.

After portacaval shunt, the size of the hepatocytes was nearly halved and the amount of fat in the cytoplasm of the liver cells decreased. Ultrastructurally, the lipid droplets remained enclosed in a double membrane. Morphologic analysis showed that the area of rough endoplasmic reticulum was reduced to 47% of the quantity found in the preoperative biopsy. The amount of smooth endoplasmic reticulum was reduced to 55% compared to the first biopsy. Free ribosomes were abundant. Glycogen particles were rare. Therefore, marked alterations in hepatocyte morphology, independent of any autolytic artifact, were observed both before and after surgery.

TABLE 1

THE EFFECT OF PORTACAVAL SHUNT ON PLASMA LIPID AND LIPOPROTEIN CONCENTRATIONS IN FAMILIAL HYPERCHOLESTEROLEMIA

	Cholesterol (mg/dl)			Triglycerides (mg/dl)	
	Total	VLDL	LDL	HDL	(mg/dl)
Normal[a] range	126–190	5–25	60–135	35–71	44–107
Preshunt	1034 ± 156	47 ± 17	957 ± 157	27 ± 9	200 ± 57
Postshunt	743 ± 37*	24 ± 6	691 ± 43*	23 ± 3	156 ± 43
% Change	28*	49	28*	15	22

Note. Plasma lipid and lipoproteins were measured five times preshunt and four times postshunt. The values represent the mean ± SE.

[a] Normal values are those reported for the 10–90 percentile for females ages 14–19 from The Lipid Research Clinics Prevalence Study [49].

* These values represent a significant difference from preshunt values ($P < 0.05$).

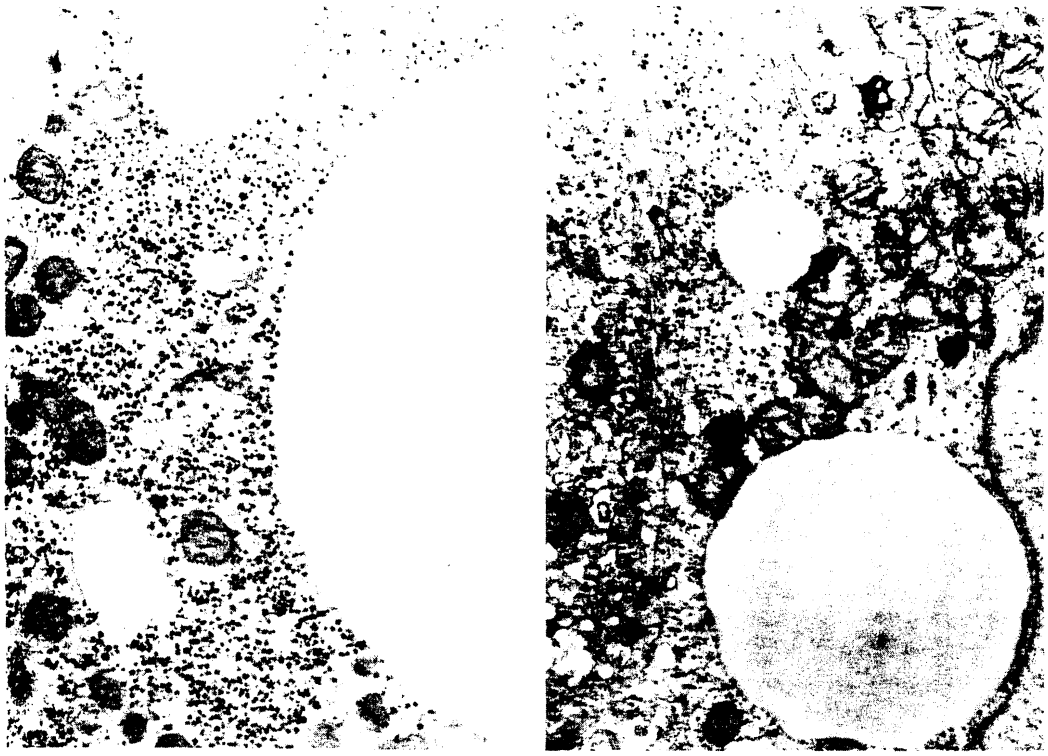

FIG. 1. Electron microscopy of hepatic biopsy specimens taken before portacaval shunt (left panel) and after portacaval shunt (right panel). The increased cytoplasmic hepatocyte lipid accumulation preshunt decreased after portacaval shunt. Magnification in both specimens is ×11,400.

The portacaval shunt was also associated with major changes in hepatic cholesterol content (Table 2). Before the portacaval shunt, the total cholesterol content in the FH liver was 1.7 times that of normal liver. Although the portacaval shunt reduced total hepatic cholesterol by 27%, the postshunt cholesterol content was still 21% higher than normal. The most striking change included the 75% decline in free cholesterol that was observed after the operation. As the free cholesterol declined, the amount of cholesterol in the esterified form increased by 79%. The normal livers had 24% of the cholesterol esterified while the FH liver preshunt had 32% of the cholesterol esterified. By performing the portacaval anastomosis, the fraction of hepatic esterified cholesterol in FH increased to 77%. Thus, the portacaval shunt had a profound effect not only on the absolute cholesterol content in the liver of TH, but also on the cholesterol distribution between free and esterified forms.

TABLE 2

EFFECT OF PORTACAVAL SHUNT ON HEPATIC CHOLESTEROL CONTENT IN FAMILIAL HYPERCHOLESTEROLEMIA

	Hepatic cholesterol (nmole/mg wet tissue)		
	Total	Free	Esterified
Normal	5.80 ± 0.46	4.99 ± 0.24	0.81 ± 0.52
Familial hypercholesterolemia			
Preshunt	9.61 ± 0.21	6.58 ± 0.24	3.03 ± 0.32
Postshunt	7.04 ± 0.19	1.62 ± 0.34	5.42 ± 0.29

Note. Three replicate samples of hepatic biopsies were measured and the values represent the mean ± SE.

Enzymes central to hepatic cholesterol metabolism were quantitated in liver biopsy specimens taken before and after surgery (Table 3). The activities of the enzymes HMG-CoA reductase, acid cholesteryl ester hydrolase, and neutral cholesteryl ester hydrolase in the preshunt liver biopsy were comparable to the activities observed in normal liver. Although the portacaval shunt had no apparent effect on neutral esterase activity, changes in both HMG-CoA reductase and acid esterase activities were observed (Table 3). A 56% decline in HMG-CoA reductase activity was paralleled by a 220% increase in acid esterase activity. Thus, portacaval shunt of blood flow from the liver appreciably altered the enzyme activities relevant to hepatic cholesterol homeostasis.

The ability of hepatic membranes to specifically bind LDL was directly determined in membranes isolated from the FH liver before and following portacaval anastomosis (Fig. 2). There was a significant reduction in LDL binding to the FH hepatic membranes compared to binding to hepatic membranes from normolipidemic subjects. After the portacaval shunt, however, the specific binding of ^{125}I-LDL to the hepatic membranes was significantly increased compared to preshunt values. Thus, portacaval shunt enhanced the hepatic membrane binding of ^{125}I-LDL.

TABLE 3

THE EFFECT OF PORTACAVAL SHUNT ON HEPATIC ENZYMATIC ACTIVITIES IN FAMILIAL HYPERCHOLESTEROLEMIA

	Enzymatic activity (% control)		
	HMG-CoA	Acid esterase	Neutral esterase
Preshunt	129 ± 26	110 ± 3	92 ± 22
Postshunt	57 ± 4	249 ± 19	102 ± 5

Note. The enzymatic activity in the FH hepatic tissue was compared to that from liver taken from three normolipidemic subjects. The control specific activities expressed as pmole/min/mg protein were HMG-CoA reductase 3.24 ± 0.75, acid esterase 71.5 ± 8.34, and neutral esterase 11.4 ± 2.1. Values represent the mean ± SE of three or four replicate samples.

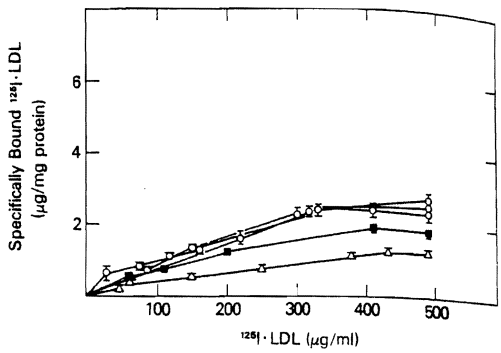

FIG. 2. Specifically bound ^{125}I-LDL to hepatic membranes from normal subjects and a familial hypercholesterolemia before and after portacaval shunt. Membranes were prepared from hepatic biopsy specimens from three normal subjects (○, N = 3), and familial hypercholesterolemic hepatic tissue preshunt (△), and postshunt (■). From 100 to 200 μg of membrane protein was added to a 75 mM NaCl, 150 mM TrisCl, 1 mM $CaCl_2$ (pH 7.5) buffer with the indicated concentrations of ^{125}I-LDL in the presence and absence of excess unlabeled LDL. Specifically bound ^{125}I-LDL, defined as the difference in ^{125}I-LDL bound in the presence and absence of excess unlabeled LDL, was normalized to the amount of membrane protein in the sample. Values represent the mean ± SE of triplicate determinations.

DISCUSSION

The extreme hypercholesterolemia and rapidly progressive premature cardiovascular disease observed in familial hypercholesterolemia have prompted the search for an effective, definitive treatment. After observing a marked decline in serum lipid concentrations with a portacaval shunt for Type I glycogen storage disease [47], Starzl and co-workers successfully employed this procedure to lower the plasma cholesterol levels in a patient with familial hypercholesterolemia [42]. Subsequent observations of lowered LDL cholesterol levels, xanthoma regression, and safety of the procedure have been reported by Starzl as well as several other investigators [6, 10, 12, 13, 25, 40, 41, 44, 54]. Thus, the use of portacaval anastomosis appeared to be one of the few successful hypocholesterolemic maneuvers in patients homozygous for FH.

The 28% reduction in total cholesterol and LDL observed in TH after portal diversion was typical of the 20–55% decline in these values

previously reported [6, 10, 12, 13, 25, 40–42, 44, 54]. This decline could occur because of a fall in the synthesis of cholesterol containing lipoproteins, an enhanced clearance of the lipoproteins from the plasma, or a combination of these two possibilities. Metabolic turnover studies of radiolabeled lipoproteins indicated that the fractional catabolic rate of FH homozygotes was significantly less than in normal individuals [5, 37, 38, 50] and that the synthesis rate of apoB into LDL was two- to fourfold normal [5, 37, 38]. Bilheimer *et al.* reported that portacaval shunt in a patient homozygous for FH enhanced the clearance of LDL from the circulation by 17% and a 48% decline was measured in the rate of LDL synthesis in a patient homozygous for FH [5]. A similar response has been reported in a patient heterozygous for FH [14]. Thus, the fall in LDL observed after portacaval shunt appeared to result from changes in both LDL synthesis and removal.

Since the mammalian liver may be important for both cholesterol and lipoprotein synthesis as well as degradation, a disruption in the blood supply rich in hepatotrophic factors would be anticipated to alter these biochemical pathways. As in the present case, the cellular structures involved with lipid and lipoprotein metabolism have consistently been shown to undergo profound morphologic changes [35, 43, 45, 46]. The reduction in hepatocyte size and the development of cytoplasmic lipid droplets in the FH liver after portacaval shunt were similar to the changes induced by portacaval shunt in the dog [45]. These anatomic alterations are paralleled by biochemical changes observed in the liver of TH after portacaval shunt. First, quantitative as well as qualitative changes in hepatic cholesterol content were observed. Total hepatic cholesterol content decreased; however, the fraction of cholesterol in the free form decreased from 68 to 23%. Second, the activity of the rate-limiting enzyme for cholesterol synthesis, HMG-CoA reductase, was reduced by more than half following the portacaval shunt. Thus, the biosynthetic pathway of cholesterol synthesis in the FH liver was shown for the first time to decline in parallel with the fall in hepatic content of total and free cholesterol following portacaval shunt.

The distribution and hydrolysis of cholesteryl ester within the FH hepatocyte may reflect aberrant metabolism of cholesteryl ester-containing lipoproteins. The LDL receptor-mediated uptake mechanism leads to lysosomal localization and degradation of LDL [8, 15]. Since TH had no high-affinity LDL receptor, delivery of LDL to cells could only occur through a pinocytotic or an alternate pathway for LDL uptake. Such an alternate pathway may lead to ineffective delivery of cholesteryl ester-rich lipoproteins to appropriate subcellular compartments. The existence of such an alternate pathway has recently been shown to be the major source of LDL delivery to the liver of the Watanabe heritable hyperlipidemic (WHHL) rabbit, the only existing animal model for FH [34]. In TH, the portacaval shunt was associated with an increase in the "receptor-independent" binding of LDL to the hepatic membranes (Fig. 2). An enhancement of LDL transport, though a less efficient alternate pathway, could account for the striking modifications observed in hepatic cholesterol metabolism.

In summary, portacaval shunt in FH has been shown to increase hepatic LDL recognition, markedly alter the intracellular enzymes central to cholesterol metabolism, and modify hepatic cholesterol concentration and distribution. These changes parallel the increased clearance of plasma LDL and reduced LDL synthesis observed in FH patients after portacaval shunt. By manipulating the metabolic consequences of the hepatic LDL receptor loss in FH, more effective therapeutic approaches to the hypercholesterolemia and accelerated atherosclerosis present in FH can be developed.

ACKNOWLEDGMENTS

We thank Dr. Lee, Dr. Warty, and Dr. Sanghvi at the University of Pittsburgh for the use of their laboratory facilities for a portion of these studies. We are also grateful to Dr. Dana Fowlkes for his effort in facilitating acquisition of postshunt tissue.

REFERENCES

1. Bachorik, P. S., Kwiterovich, P. O., and Cook, J. C. Isolation of a porcine liver plasma membrane fraction that binds low density lipoproteins. *Biochemistry* **17:** 5287, 1978.
2. Basu, S. K., Goldstein, J. L., and Brown, M. S. Characterization of low density lipoprotein receptor in membranes prepared from human fibroblasts. *J. Biol. Chem.* **253:** 3852, 1978.
3. Beg, Z. H., Stonik, J. A., and Brewer, H. B., Jr. 3-Hydroxy-3-methylglutaryl coenzyme A reductase: Regulation of enzymatic activity by phosphorylation and dephosphorylation. *Proc. Natl. Acad. Sci. USA* **75:** 3678, 1982.
4. Bilheimer, D. W., Eisenberg, S., and Levy, R. I. The metabolism of very low density lipoproteins. I. Preliminary *in vitro* and *in vivo* observations. *Biochim. Biophys. Acta* **260:** 212, 1972.
5. Bilheimer, D. W., Goldstein, J. L., Grundy, S. M., and Brown, M. D. Reduction in cholesterol and low density lipoprotein synthesis after portacaval shunt surgery in a patient with homozygous familial hypercholesterolemia. *J. Clin. Invest.* **56:** 1420, 1975.
6. Blanchard, H., Bensoussan, A. L., Collin, P. P., Desjardins, J. G., Ouimet, A., and Letarte, J. Terminolateral portacaval anastomosis in Type II homozygous familial hypercholesterolemia. *Child. Pediatr.* **20:** 221, 1979.
7. Brown, M. S., and Goldstein, J. L. Familial hypercholesterolemia: Defective binding of lipoproteins to cultured fibroblasts associated with impaired regulation 3-hydroxy-3-methylglutaryl coenzyme A reductase activity. *Proc. Natl. Acad. Sci. USA* **71,** 788, 1974.
8. Brown, M. D., Kovanen, P. T., and Goldstein, J. L. Regulation of plasma cholesterol by lipoprotein receptors. *Science (Washington, D. C.)* **212:** 628, 1981.
9. Carew, T. E., Pittman, R. C., and Steinberg, D. Tissue sites of degradation of native and reductively methylated [^{14}C]sucrose-labeled low density lipoprotein in rats. *J. Biol. Chem.* **257:** 8001, 1982.
10. Cywes, S., Davies, M. R. Q., Louw, J. H., Berger, G. M. B., Bonnici, F., and Joffe, H. S. Portacaval shunt in two patients with homozygous Type II hyperlipoproteinemia. *S. African Med. J.* **50:** 239, 1976.
11. Dietschy, J. D. M., and Wilson, J. R. Regulation of cholesterol metabolism. *N. Engl. J. Med.* **282:** 1128, 1241, 1970.
12. Farriaux, J. P., Ribet, M., Bertrand, M., Higgins, M., Mazzuca, M., and Luychy, A. Treatment of Type II familial hypercholesterolemia with portacaval anastomosis. *Arch. Fr. Pediatr.* **33:** 745, 1976.
13. Forman, M. B., Baker, S. G., Mieny, D. J., *et al.* Treatment of homozygous familial hypercholesterolemia with portacaval shunt. *Atherosclerosis* **41:** 349, 1982.
14. Ginsberg, H., Davidson, N., Le, N. A., Gibson, J., Ahrens, E. H., and Brown, W. V. Marked overproduction of low density lipoprotein B in a subject with heterozygous familial hypercholesterolemia: Effect of portacaval shunting. *Biochim. Biophys. Acta* **712:** 250, 1982.
15. Goldstein, J. L., and Brown, M. S. Binding and degradation of low density lipoproteins by cultured human fibroblasts. *J. Biol. Chem.* **210:** 5153, 1974.
16. Harders-Spengel, K., Wood, C. B., Thompson, G. R., Myant, N. B., and Soutar, A. K. Difference in saturable binding of low density lipoprotein to liver membranes from normocholesterolemic subjects and patients with heterozygous familial hypercholesterolemia. *Proc. Natl. Acad. Sci. USA* **78:** 6355, 1982.
17. Havel, R. J., Eder, H. A., and Bragdon, J. H. The distribution and chemical composition of ultracentrifugally separated lipoproteins in human serum. *J. Clin. Invest.* **34:** 1345, 1955.
18. Havel, R. J., Goldstein, J. L., and Brown, M. S. In P. K. Bondy and L. E. Rosenberg (Eds.), *Metabolic Control and Disease.* Philadelphia: Saunders, 1980. Pp. 393–494.
19. Hay, R. V., Pottenger, L. A., Reingold, A. L., and Getz, G. S. Degradation of ^{125}I-labeled serum low density lipoprotein in normal and estrogen-treated male rats. *Biochem. Biophys. Res. Commun.* **44:** 1471, 1971.
20. Heider, J. G., and Boyette, R. L. The picomole determination of free and total cholesterol in cells in culture. *J. Lipid Res.* **19:** 514, 1978.
21. Hoeg, J. H., Demosky, S. J., and Brewer, H. B., Jr. Characterization of neutral and acid ester hydrolase in Wolman's Disease. *Biochim. Biophys. Acta* **711:** 59, 1982.
22. Hoeg, J. M., Demosky, S. J., Jr., Schaefer, E. J., Starzl, T. E., and Brewer, H. B., Jr. Characterization of hepatic low density lipoprotein binding and cholesterol metabolism in normal and familial hypercholesterolemic subjects. *J. Clin. Invest.* **73:** 429, 1984.
23. Hui, D. Y., Innerarity, T. A., and Mahley, R. W. Lipoprotein binding to canine hepatic membranes; metabolically distinct ApoE and ApoB, E receptors. *J. Biol. Chem.* **256,** 5646, 1981.
24. Khachadurian, A. K. The inheritance of essential familial hypercholesterolemia. *Amer. J. Med.* **37:** 402, 1964.
25. Korgh, L., and Wickens, J. T. Portacaval shunt for hypercholesterolemia. *S. African Med. J.* **48:** 2302, 1974.
26. Kovanen, P. T., Bilheimer, D. W., Goldstein, J. L., Jaramillo, J., and Brown, M. S. Regulatory role for hepatic low density lipoprotein receptors *in vivo* in the dog. *Proc. Natl. Acad. Sci. USA* **78:** 1194, 1981.
27. Kovanen, P. T., Brown, M. S., Basu, S. K., Bilheimer, D. W., and Goldstein, J. L. Saturation and suppression of hepatic lipoprotein receptors: A mechanism for the hypercholesterolemia of cholesterol-fed rabbits. *Proc. Natl. Acad. Sci. USA* **78:** 1396, 1981.
28. Kovanen, P. T., Brown, M. S., and Goldstein, J. L. Increased binding of low density 17 α-ethinylestradiol. *J. Biol. Chem.* **254:** 11367, 1979.

29. Loud, A. V. A quantitative sterological description of the ultrastructure of normal rat liver parenchymal cells. *J. Cell Biol.* **37**: 27, 1968.
30. Lowry, O. H., Rosebrough, N. J., Farr, A. L., and Randall, R. J. Protein measurement with the Folin phenol reagent. *J. Biol. Chem.* **193**: 265, 1951.
31. MacFarlane, A. S. Efficient trace labeling of proteins with iodine. *Nature (London)* **182**: 53, 1958.
32. Pesce, M. S., and Bodourian, S. H. Enzymatic rate method for measuring cholesterol in serum. *Clin. Chem.* **22**: 2042, 1976.
33. Pittman, R. C., Attie, A. D., Carew, T. E., and Steinberg, D. Tissue sites of degradation of low density lipoprotein: Application of a method for determining the fate of plasma proteins. *Proc. Natl. Acad. Sci. USA* **76**: 5345, 1979.
34. Pittman, R. C., Carew, T. E., Attie, A. D., Witztum, J. L., Watanabe, Y., and Steinberg, D. Receptor-dependent and receptor-independent degradation of low density lipoproteins in normal rabbits and in receptor-deficient mutant rabbits. *J. Biol. Chem.* **257**: 7997, 1982.
35. Putnam, C. W., Porter, K. A., and Starzl, T. E. Hepatic encephalopathy and light and electron micrographic changes of the baboon liver after portal diversion. *Ann. Surg.* **184**: 155, 1976.
36. Redding, C. M., and Steinberg, D. Studies on the synthesis and secretion of serum lipoproteins by rat liver slices. *J. Clin. Invest.* **39**: 1560, 1960.
37. Reichl, D. L., Simons, L. A., and Myant, N. B. The metabolism of low density lipoprotein in a patient with familial hyperbetalipoproteinemia. *Clin. Sci. Mol. Med.* **47**: 635, 1974.
38. Simons, L. A., Reichl, D. L., Myant, N. B., and Mancini, M. The metabolism of the apoprotein of plasma low density lipoprotein in familial hyperbetalipoproteinemia in the homozygous form. *Atherosclerosis* **21**: 283, 1975.
39. Snedecor, G. W., and Cochran, W. G. *Comparison of Two Samples. Statistical Methods.* Ames, Iowa: Iowa State Univ. Press, 1980. Pp. 83–106.
40. Soutar, A. K., Myant, N. B., and Thompson, G. R. Measurement of apolipoprotein B turnover in very low and low density lipoprotein in familial hypercholesterolemia. *Atherosclerosis* **28**: 247, 1977.
41. Starzl, T. E., Chase, H. P., Ahrens, E. H., *et al.* Portacaval shunt in patients with familial hypercholesterolemia. *Ann. Surg.* **198**: 273, 1983.
42. Starzl, T. E., Chase, H. P., Putnam, C. W., and Porter, K. A. Portacaval shunt in hyperlipoproteinemia. *Lancet* **2**: 940, 1973.
43. Starzl, T. E., Francavilla, A., and Halgrimson, C. G. The origin, hormonal nature and action hepatotrophic substances in portal venous blood. *Surg. Gynecol. Obstet.* **137**: 179, 1973.
44. Starzl, T. E., Koef, P. J., and Weil, R., III. Portacaval shunt for Type II hyperlipidemia. *Atherosclerosis I: Proceedings of the Fifth International Symposium of Atherosclerosis.* Berlin: Springer-Verlag, 1980. P. 450.
45. Starzl, T. E., Lee, I. Y., Porter, K. A., and Putnam, C. W. The influence of portal blood upon lipid metabolism in normal and diabetic dogs and baboons. *Surg. Gynecol. Obstet.* **140**: 381, 1975.
46. Starzl, T. E., Porter, K. A., Watanabe, K., and Putnam, C. W. The effects of insulin, glucagon, and insulin/glucagon infusions upon liver morphology and cell division after complete portacaval shunt in dogs. *Lancet* **1**: 821, 1976.
47. Starzl, T. E., Putnam, C. W., Porter, K. A., Halgrimson, C. G., Corman, J., Brown, V. L., Gotlin, R. W., Rodgerson, D. O., and Greene, H. L. Portal diversion for the treatment of glycogen storage disease in humans. *Ann. Surg.* **178**: 525, 1973.
48. Stein, Y., and Stein, O. In G. Scheltler and A. Weizel (Eds.), *Atherosclerosis III* Berlin: Springer-Verlag, 1974. Pp. 652–657.
49. *The Lipid Research Clinic Population Studies Data Book: The Prevalence Study.* NIH Publication No. 80-1527, 1980. Pp. 1–136.
50. Thompson, G. R., Soutar, A. K., Spengel, F. A., Jadhav, A., Gavigan, S. J. P., and Myant, N. B. Defects of receptor-mediated low density lipoprotein catabolism in homozygous familial hypercholesterolemia and hypothyroidism *in vivo*. *Proc. Natl. Acad. Sci. USA* **78**: 2591, 1981.
51. Tolleshaug, H., Hobgood, K. K., Brown, M. S., and Goldstein, J. L. The LDL receptor locus in familial hypercholesterolemia: Multiple mutations disrupt transport and processing of a membrane receptor. *Cell* **32**: 941, 1983.
52. Wahlenfeld, A. N. *Methods of Enzymatic Analysis.* New York: Academic Press, 1974. P. 1831.
53. Warner, T. G., Dambach, L. M., Shin, J. H., and O'Brien, J. S. Separation and characterization of the acid lipase and neutral esterases in human liver. *Amer. J. Hum. Genet.* **32**: 869, 1980.
54. Weglicki, W. B., Ganda, O. P., Soeldner, J. S., Murawski, B. J., Cohn, L. H., and Couch, N. P. Portacaval diversion of severe hypercholesterolemia. *Arch. Surg.* **112**: 634, 1977.
55. Windler, E. E. T., Kovanen, P. O. T., Chao, Y. S., Brown, M. D., Havel, R. J., and Goldstein, J. L. The estradiol stimulated lipoprotein receptor of rat liver. *J. Biol. Chem.* **255**: 10464, 1980.